Geologic Hazards Potentially Affecting the SR-520 Bridge and the Alaskan Way Viaduct

by

Timothy J. Walsh

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Division of Geology and Earth Resources

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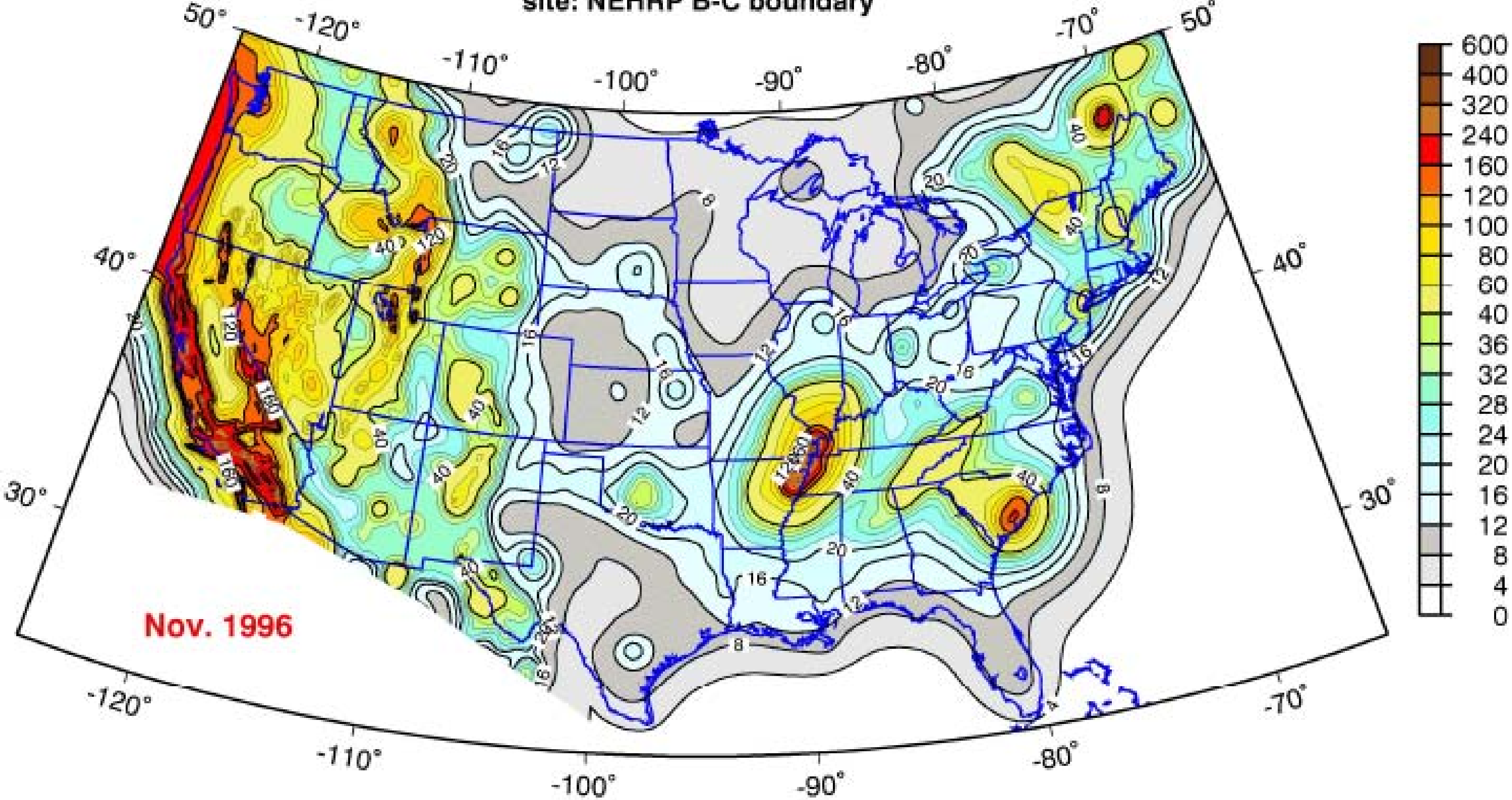
Ron Teissere - State Geologist

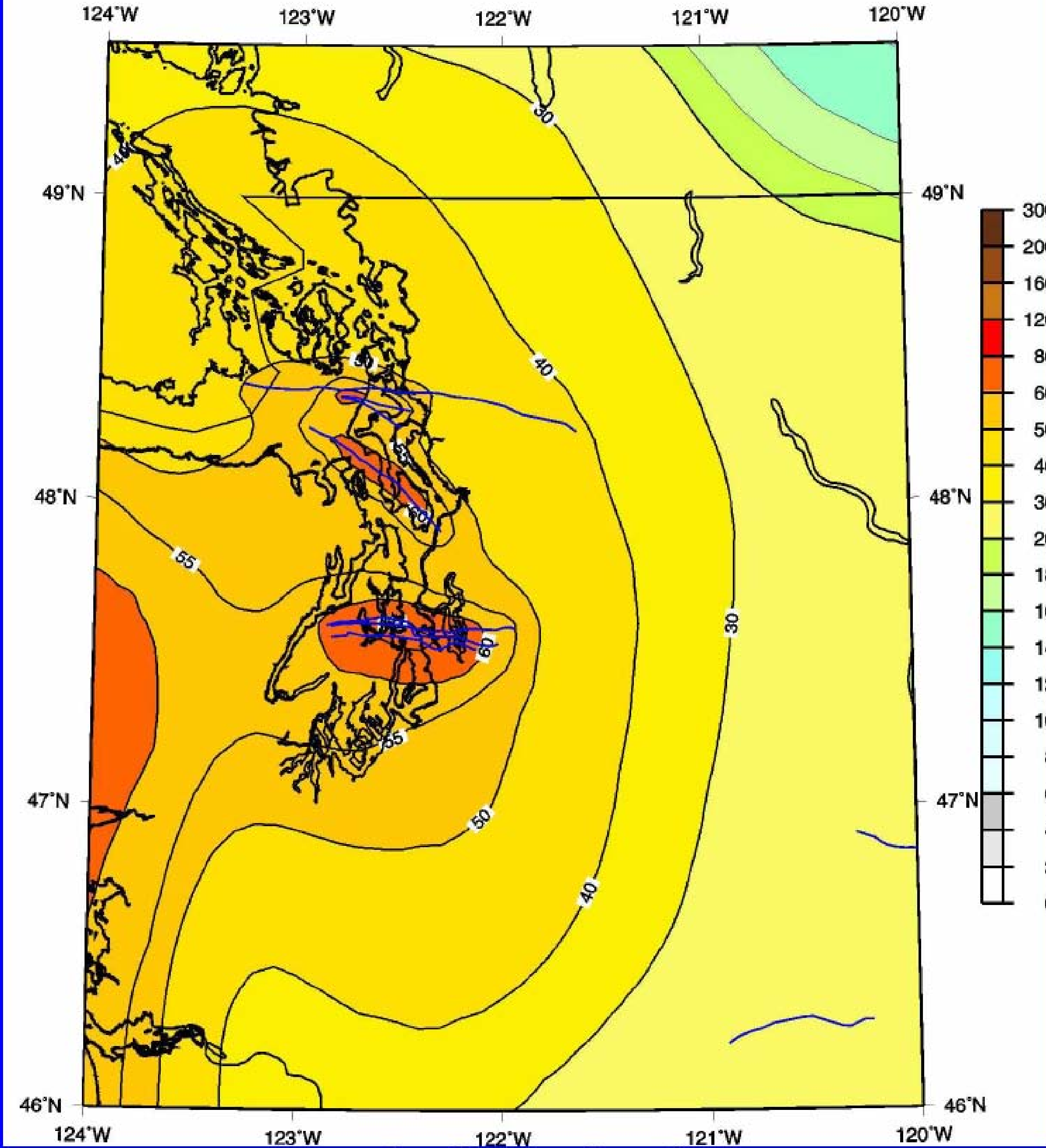
0.2 sec Spectral Accel. (%g) with 2% Probability of Exceedance in 50 Years

site: NEHRP B-C boundary



U.S. Geological Survey
National Seismic Hazard Mapping Project

From 2002 USGS National Seismic Hazard Map
PGA (%g) with 2% Prob. Of Exceedance in 50 Years



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From

THE COTTAGE LAKE AEROMAGNETIC LINEAMENT: A POSSIBLE ONSHORE EXTENSION OF THE SOUTHERN WHIDBEY ISLAND FAULT, WASHINGTON

By

Richard J. Blakely, Brian L. Sherrod, Ray E. Wells, Craig S. Weaver, David H. McCormack, Kathy G. Troost, and Ralph A. Haugerud

U.S.G.S. Open-File Report 2004-1204

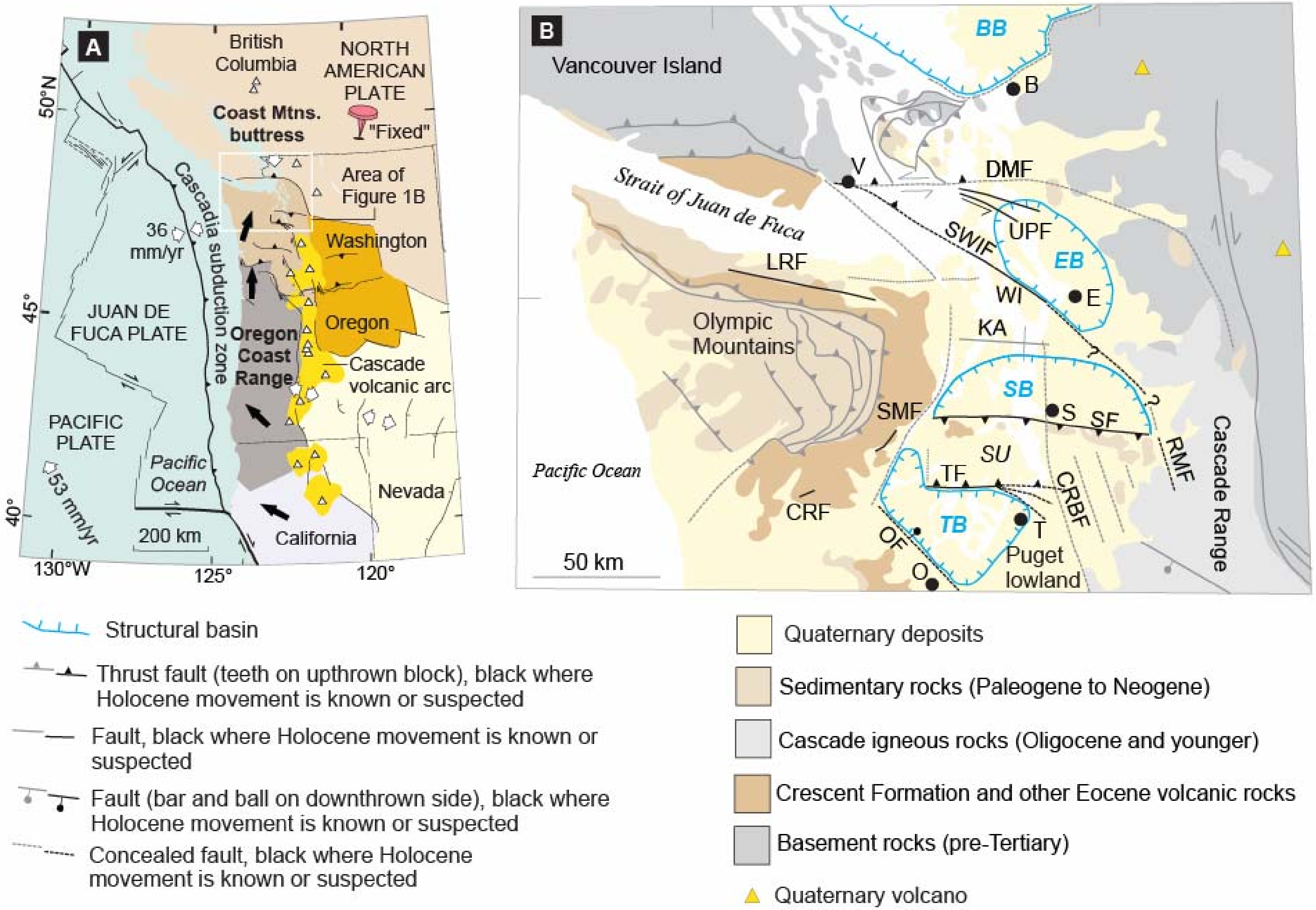

Figure 4. A.) Tectonic setting of Cascadia subduction zone. Western Washington region (brown), between fixed North America and Oregon Coast Range, is undergoing transpression. This transpression creates folds and reverse faults across Puget Sound. Bold arrows indicate motions of tectonic blocks inferred from geologic and geodetic data. Modified from Wang and others (2003) and Wells and others (1998). Box shows area of B.

B.) Schematic geologic map of northwestern Washington showing the Puget Lowland and flanking Cascade Mountains, Coast Range, and Olympic Mountains. Abbreviations for cities are as follows: B, Bellingham; O, Olympia; S, Seattle; T, Tacoma; V, Victoria. Abbreviations for faults (heavy lines) and other geologic features are as follows: BB, Bellingham Basin; CRBF, Coast Range Border fault; CRF, Canyon River fault; DAF, Darrington fault; DMF, Devils Mountain fault: E, Everett; EB, Everett Basin; KA, Kingston arch; LRF, Little River fault; OF, Olympia fault; RMF, Rattlesnake Mountain fault; SB, Seattle basin; SF, Seattle fault; SMF, Saddle Mountain faults; SU, Seattle uplift; SWIF, southern Whidbey Island fault; TB, Tacoma basin; TF, Tacoma fault; UPF, Utsalady Point and Strawberry Point faults. Geology from Walsh and others (1987), Dragovich and others, 2002, and Johnson and others 2004.

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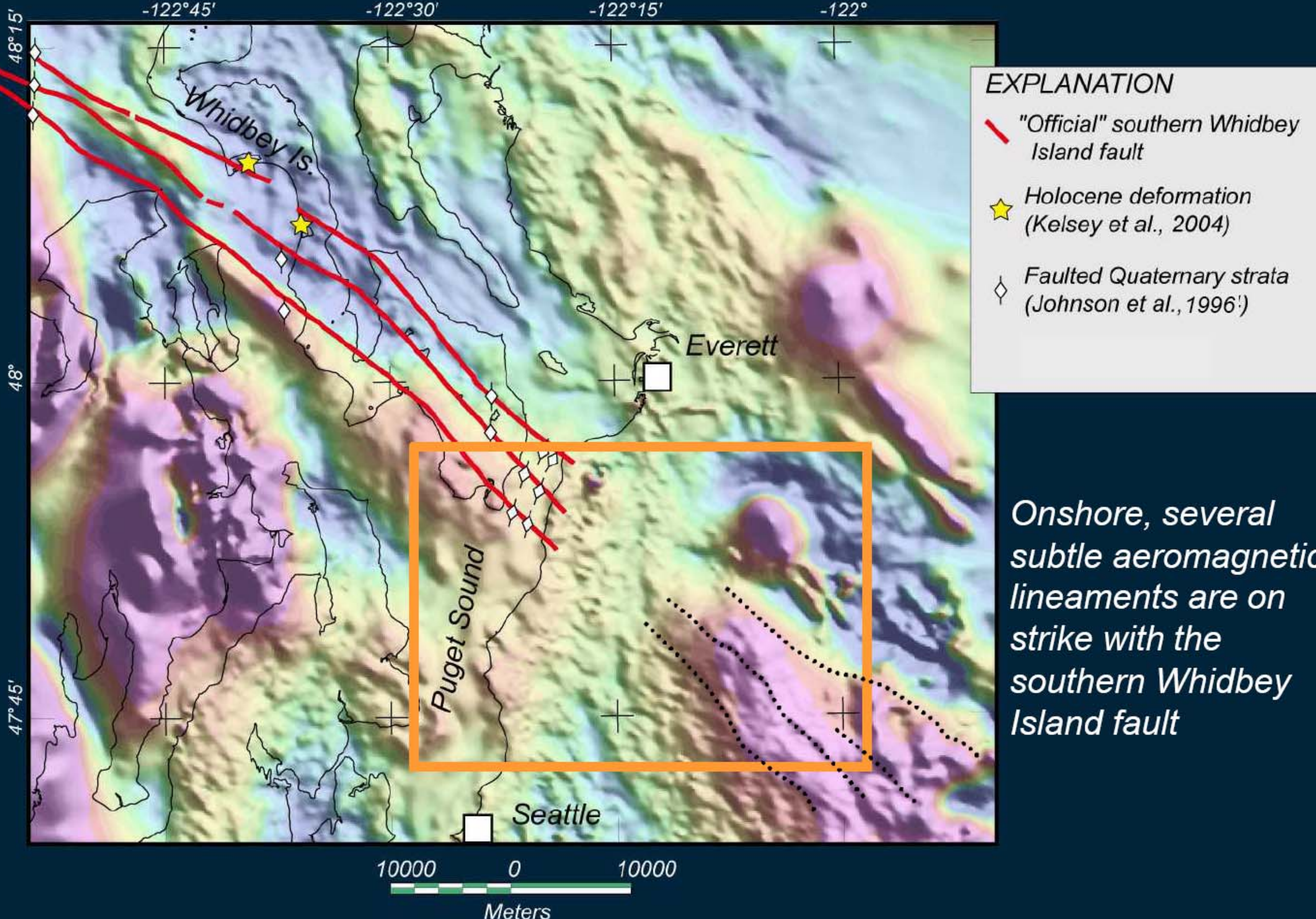
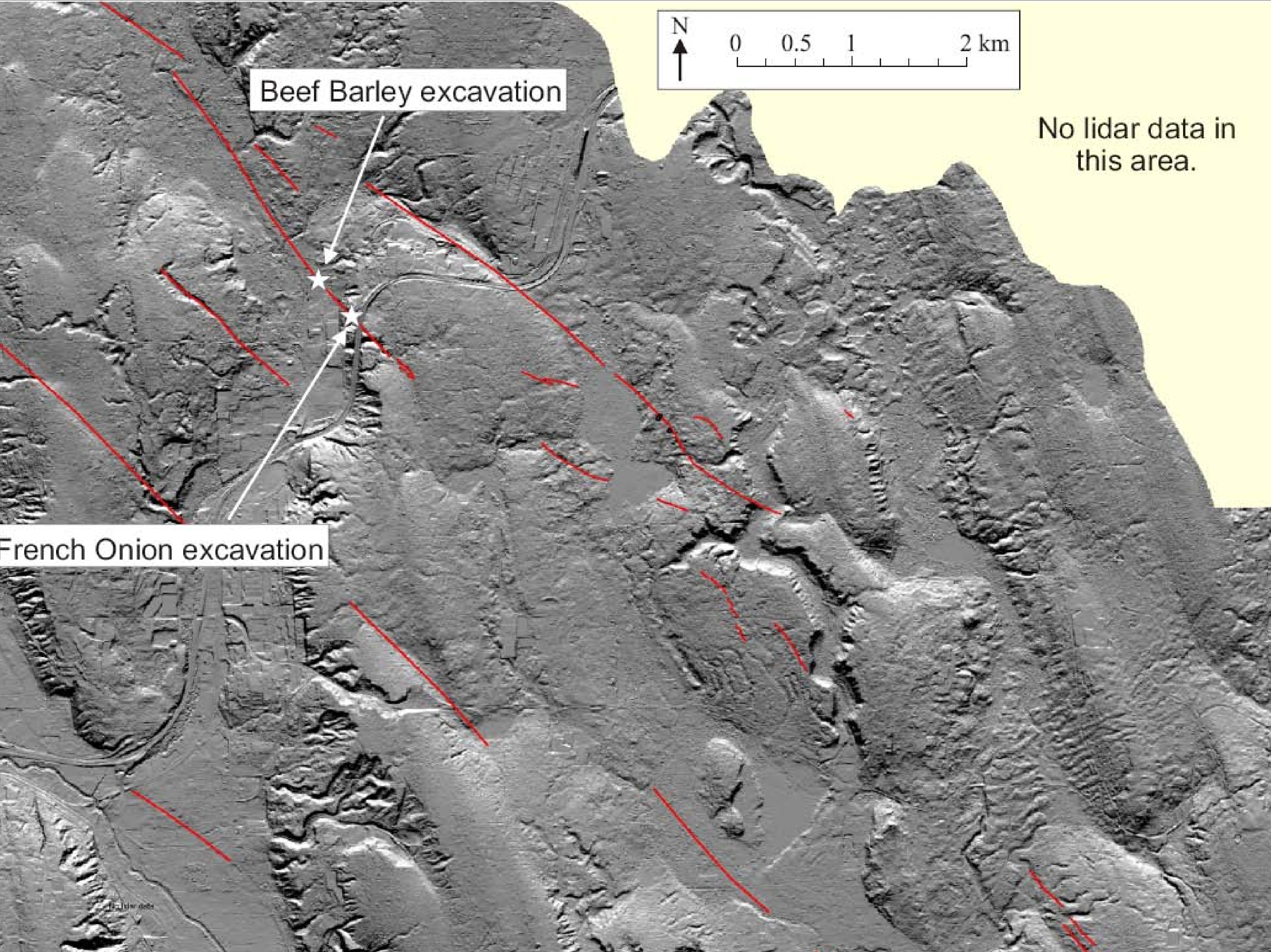
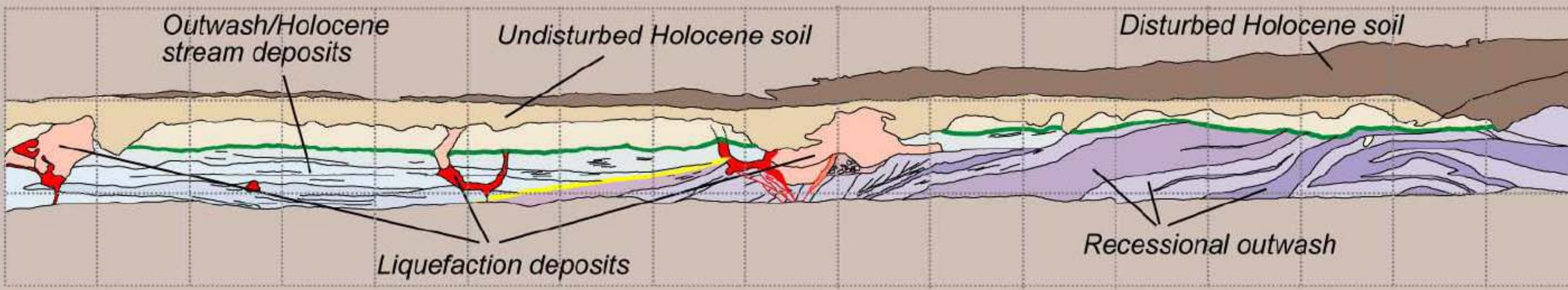
Aeromagnetic Anomalies and the Southern Whidbey Island Fault

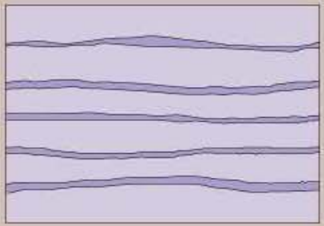


Onshore, several subtle aeromagnetic lineaments are on strike with the southern Whidbey Island fault

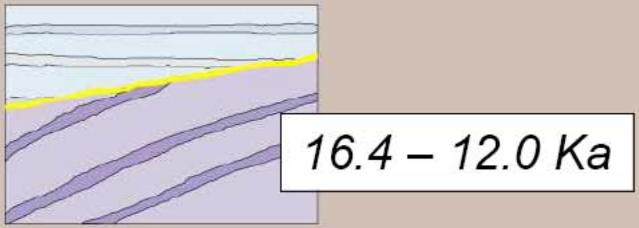

N
0 0.5 1 2 km
Beef Barley excavation
No lidar data in
this area.
French Onion excavation

Beef Barley Trench Log

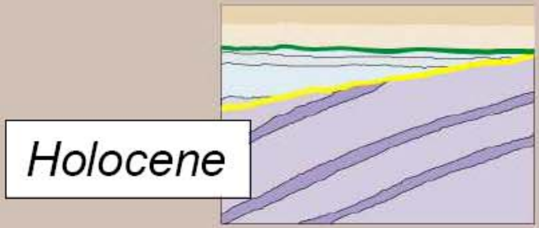




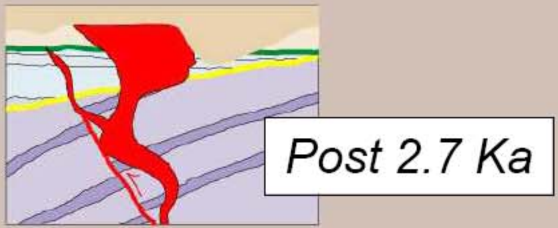
Pre-event 1: Recessional outwash (~16 ka to ~13 k)



Event 1: Folding of outwash and deposition of younger outwash/Holocene fluvial deposits (angular unconformity = yellow line)

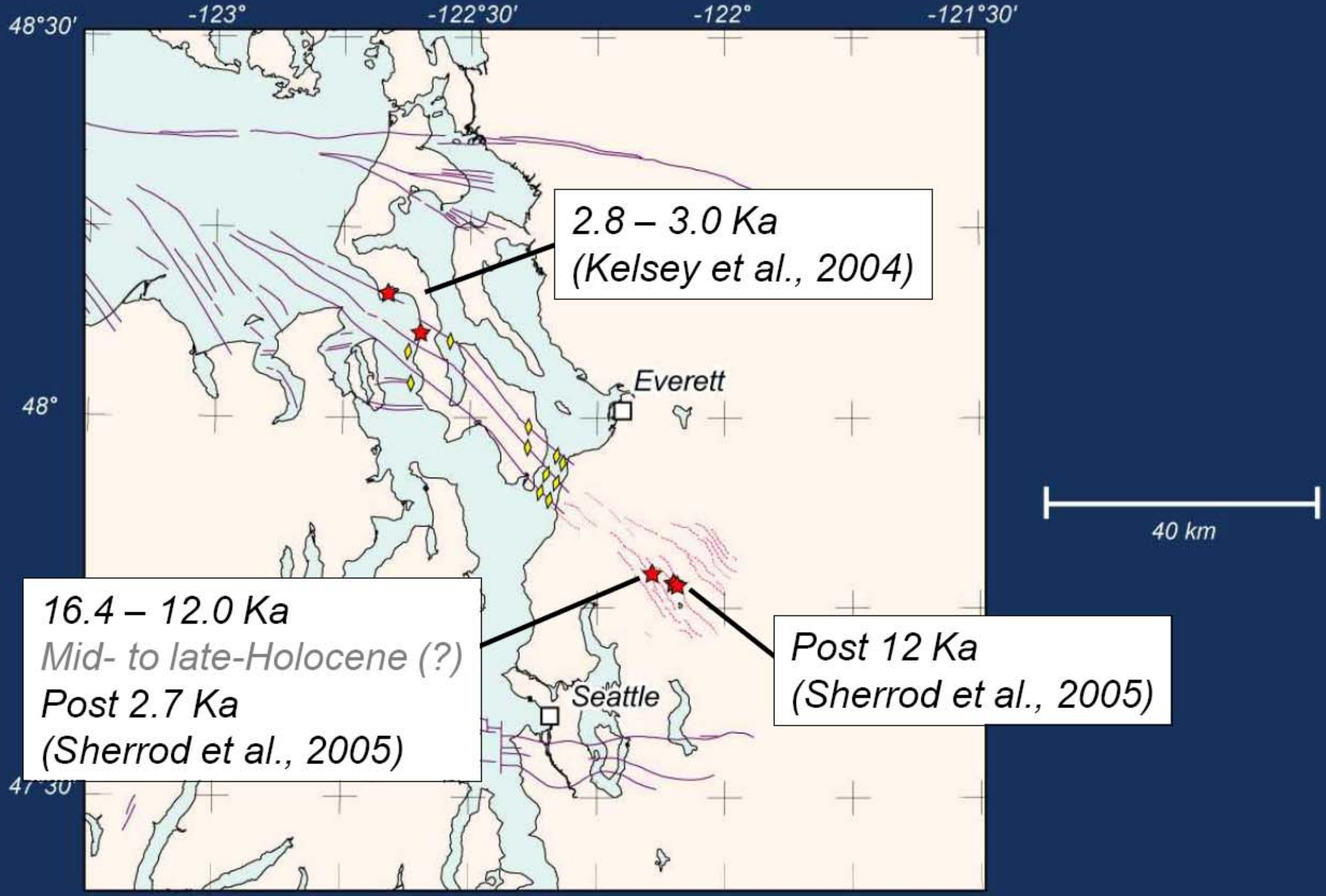


Possible Event 2: Erosion of younger outwash/Holocene fluvial deposits (younger unconformity = green line)

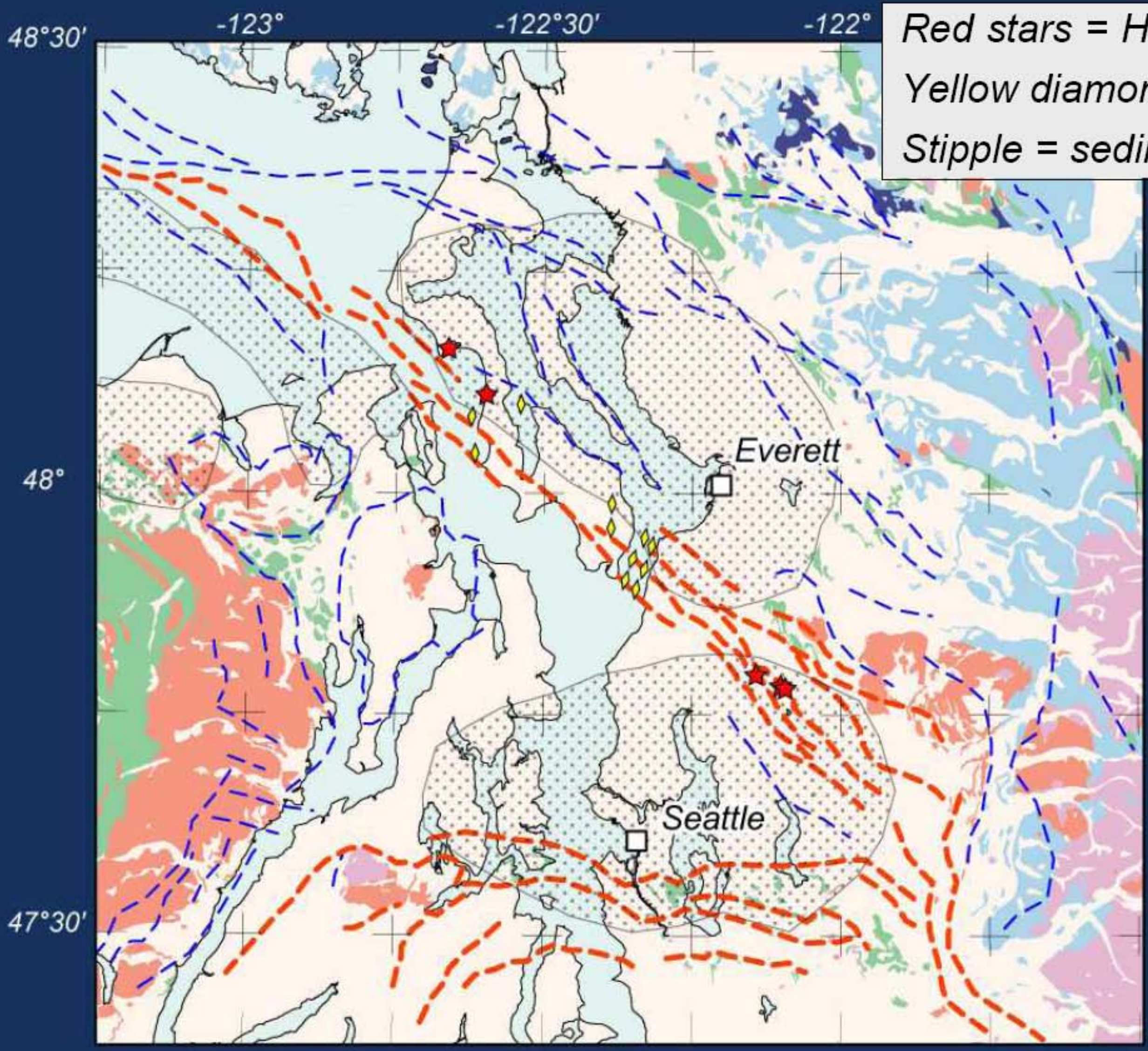


Event 3: Faulting and liquefaction, likely accompanied by a small amount of folding (<50 cm)

Holocene Deformation, Southern Whidbey Island Fault



Connecting the Dots



Red stars = Holocene deformation

Yellow diamonds = faulted Quat. Strata

Stipple = sedimentary basin

Quaternary deposits

Tertiary sedimentary rocks

Tertiary volcanic rocks

Tertiary intrusive rocks

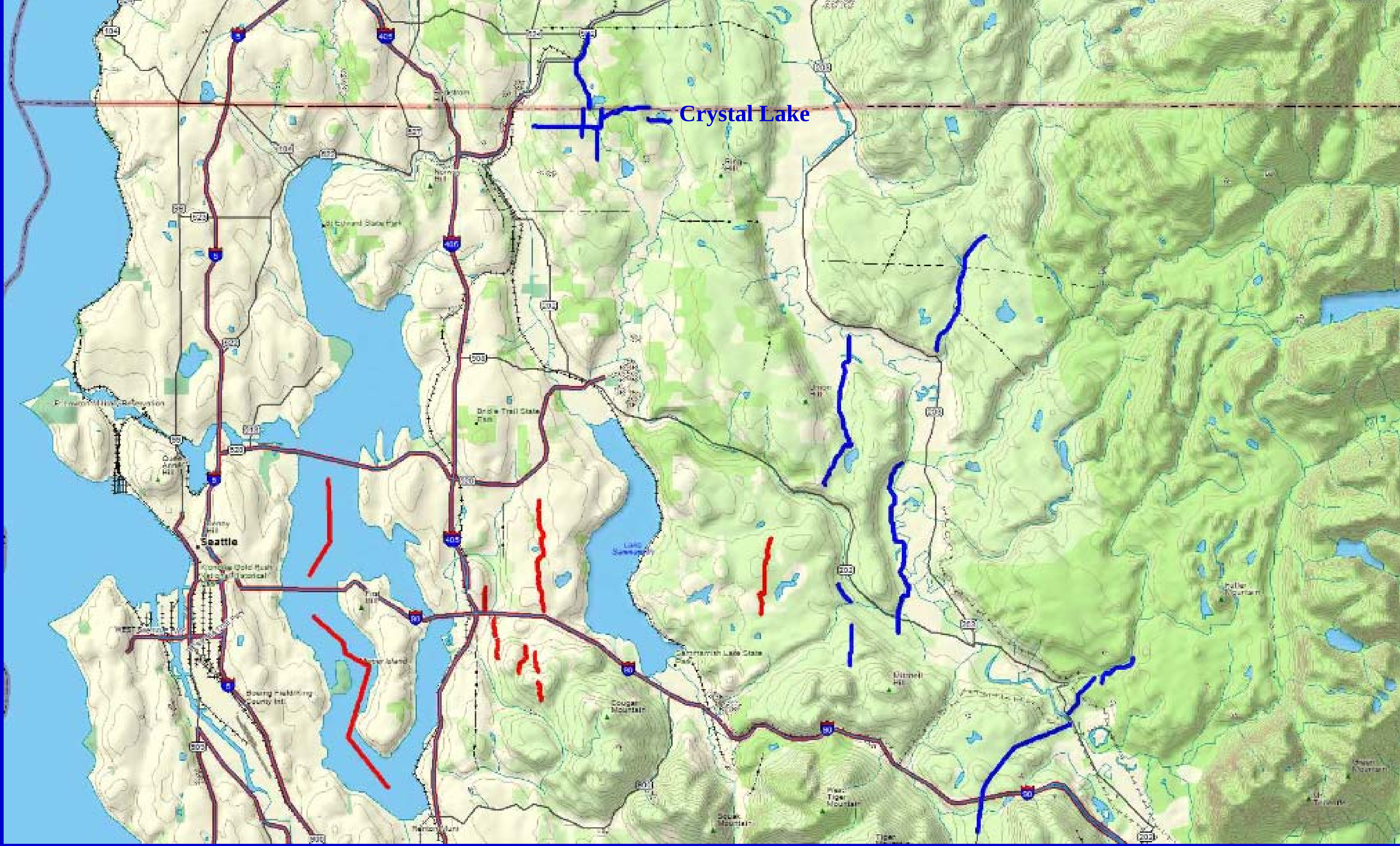
Pre-Tertiary ultramafic rocks

Other pre-Tertiary rocks

40 km

Speculation: The Rattlesnake Mt. fault splays into the southern Whidbey Island and Seattle fault zones.

Geology generalized from Dragovich et al. (2002)



New seismic reflection profiles by Lee Liberty,

Boise State University

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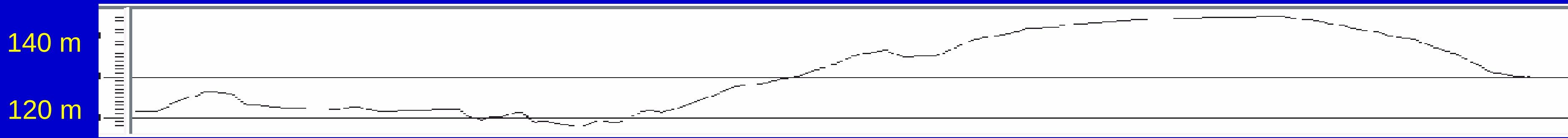
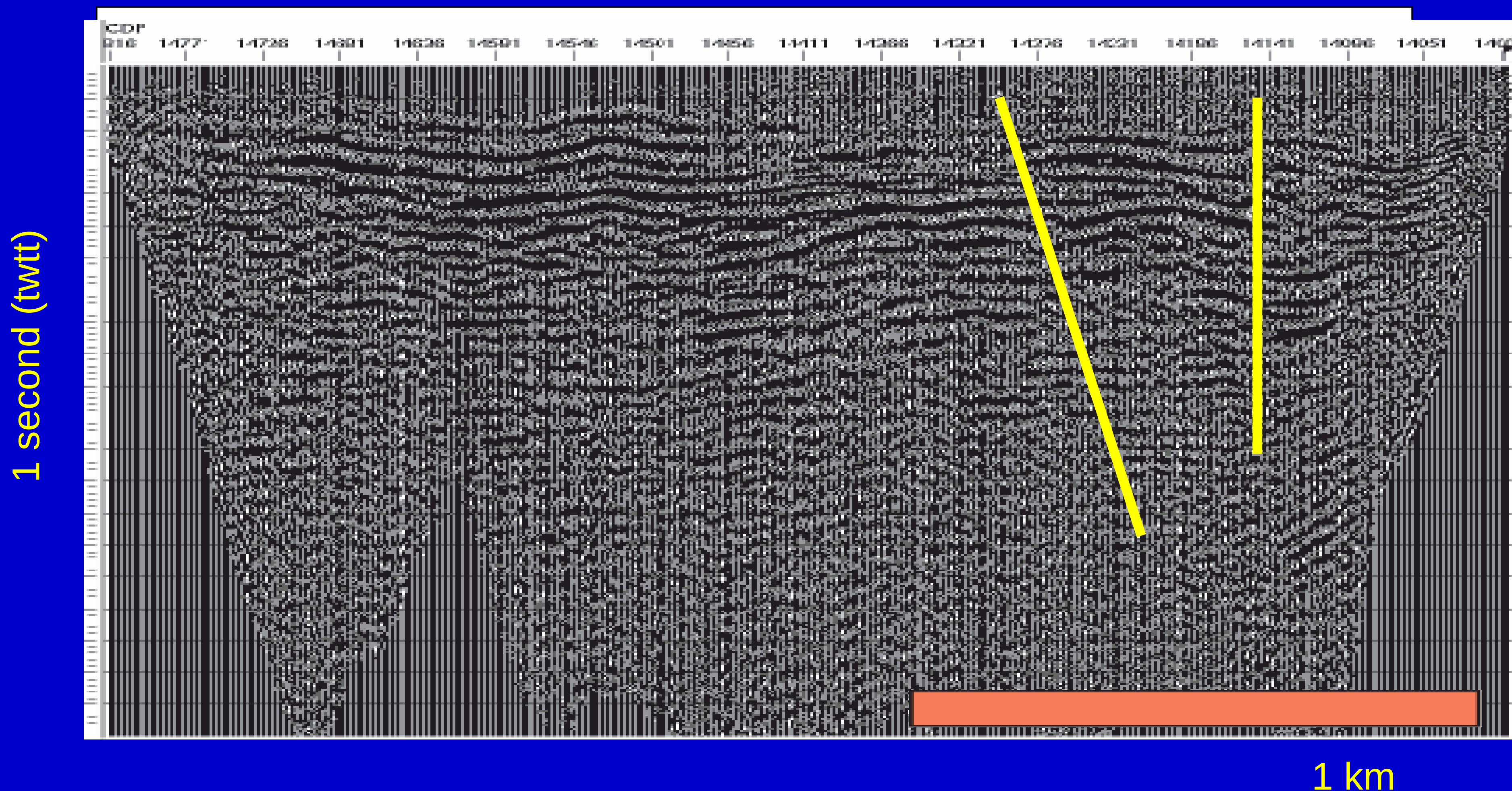
Crystal Lake seismic profile with elevation





From Lee Liberty, Boise State University

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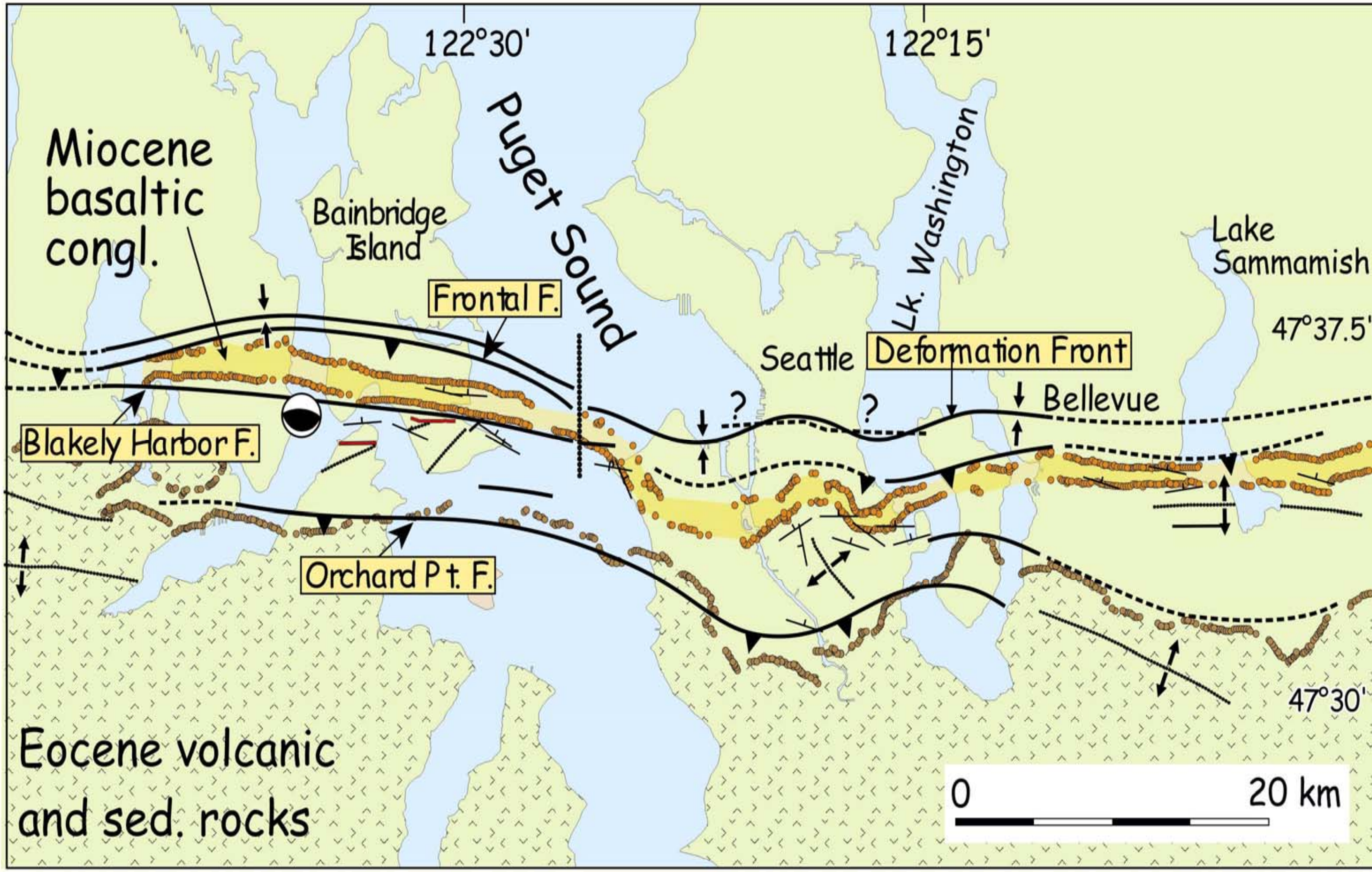
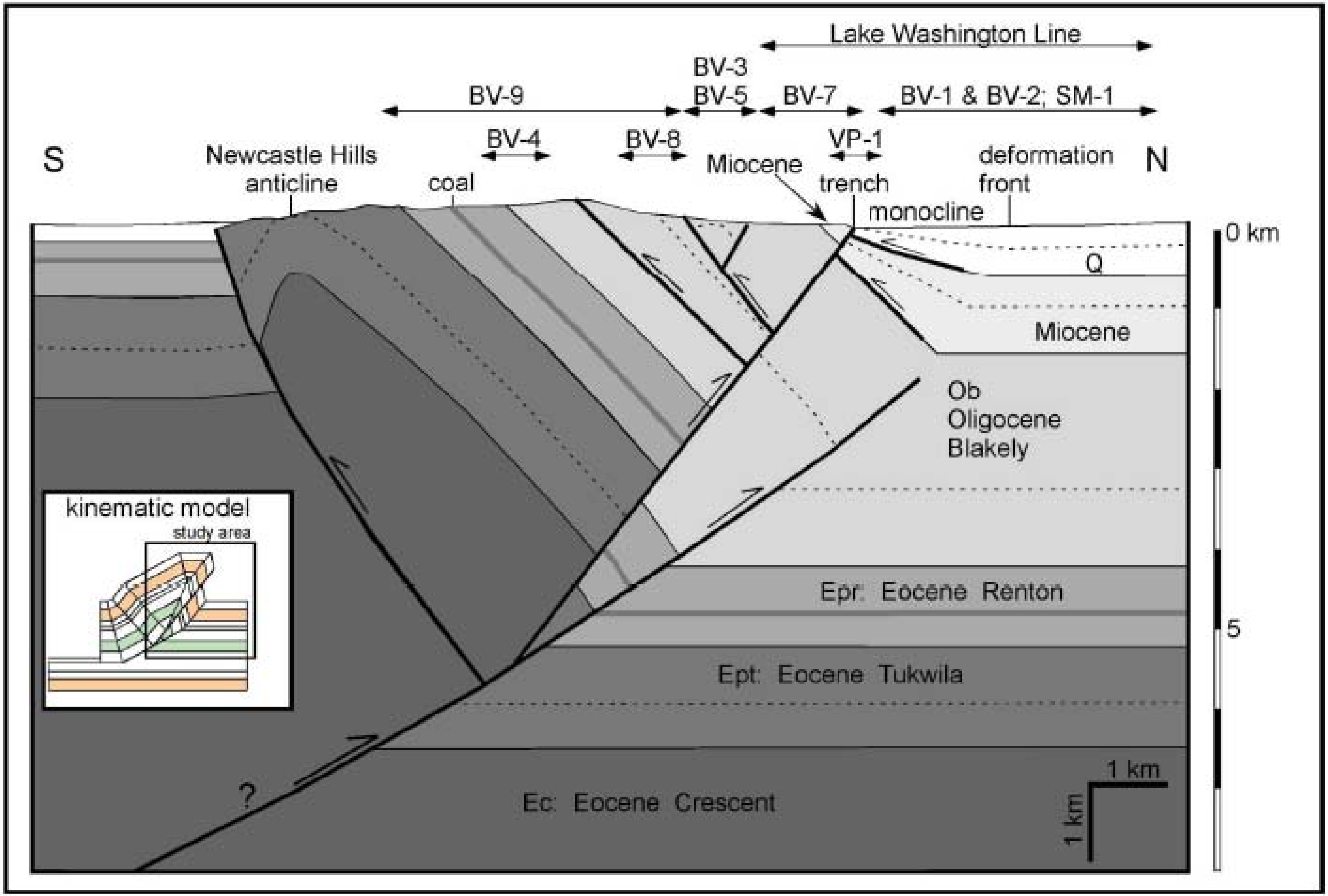
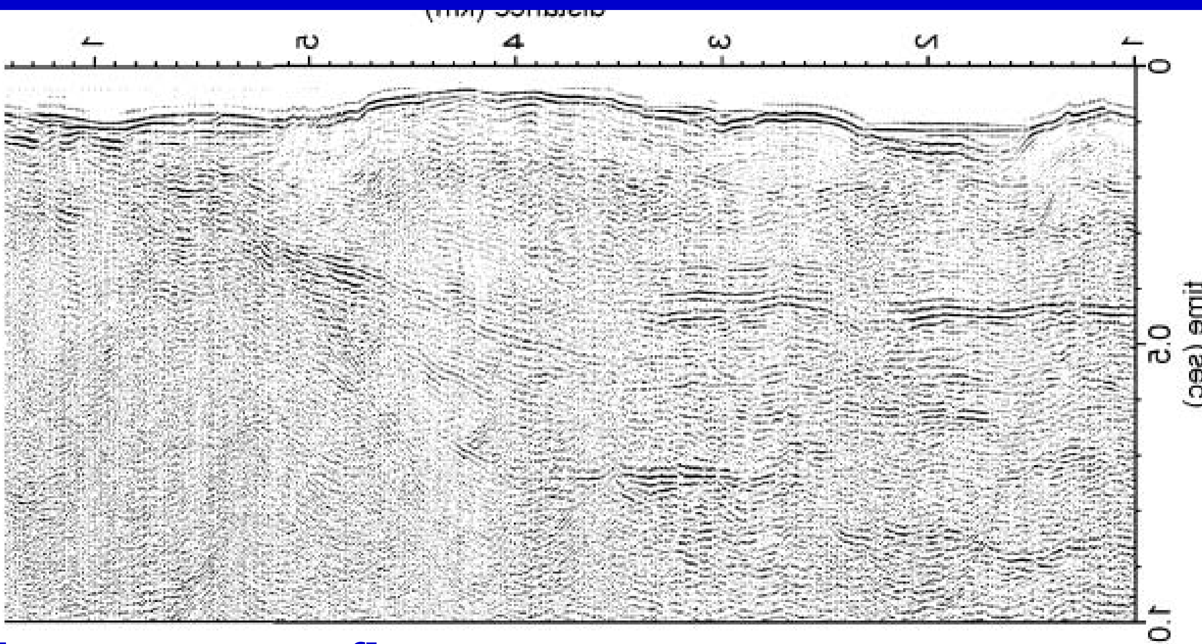


Interpreted Aeromagnetic Map of the Seattle Fault Zone

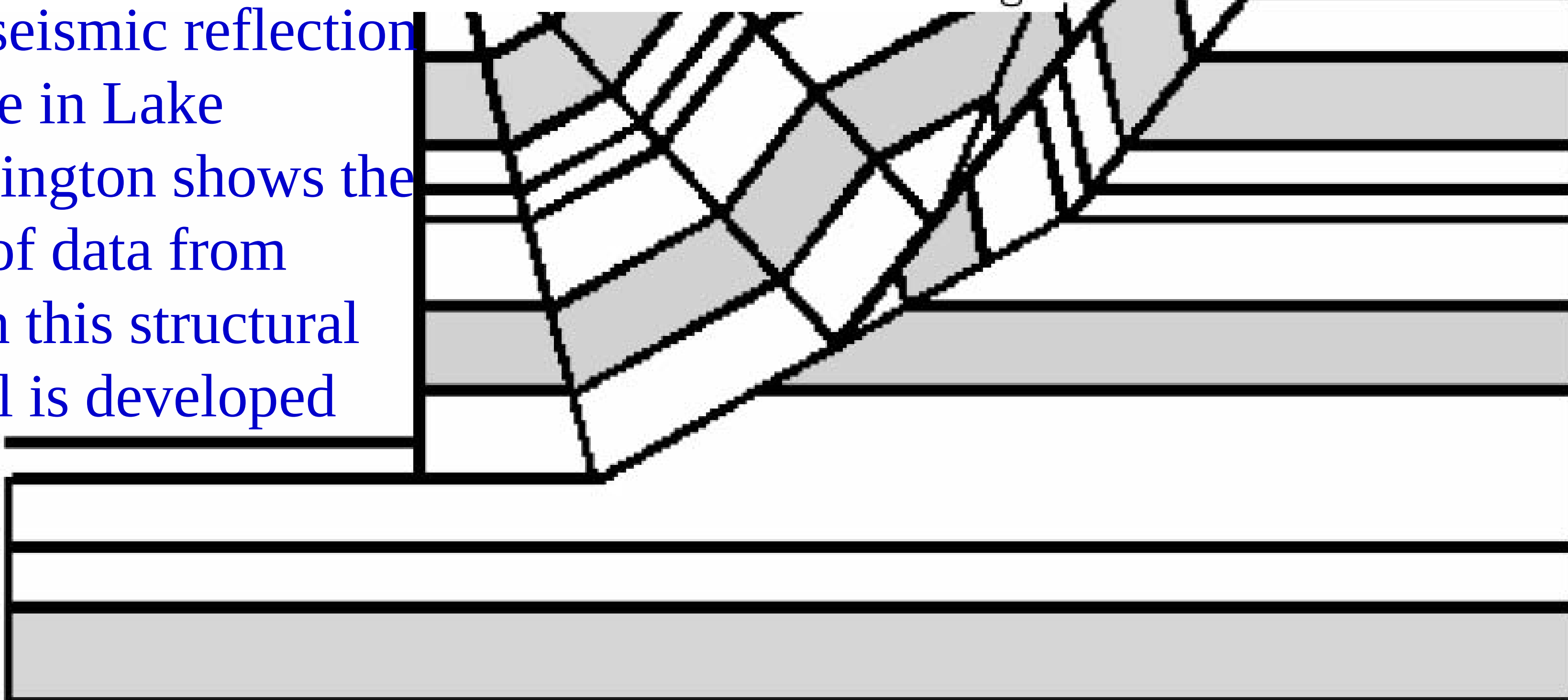
Epicenter, M 4.9
Bainbridge Island earthquake

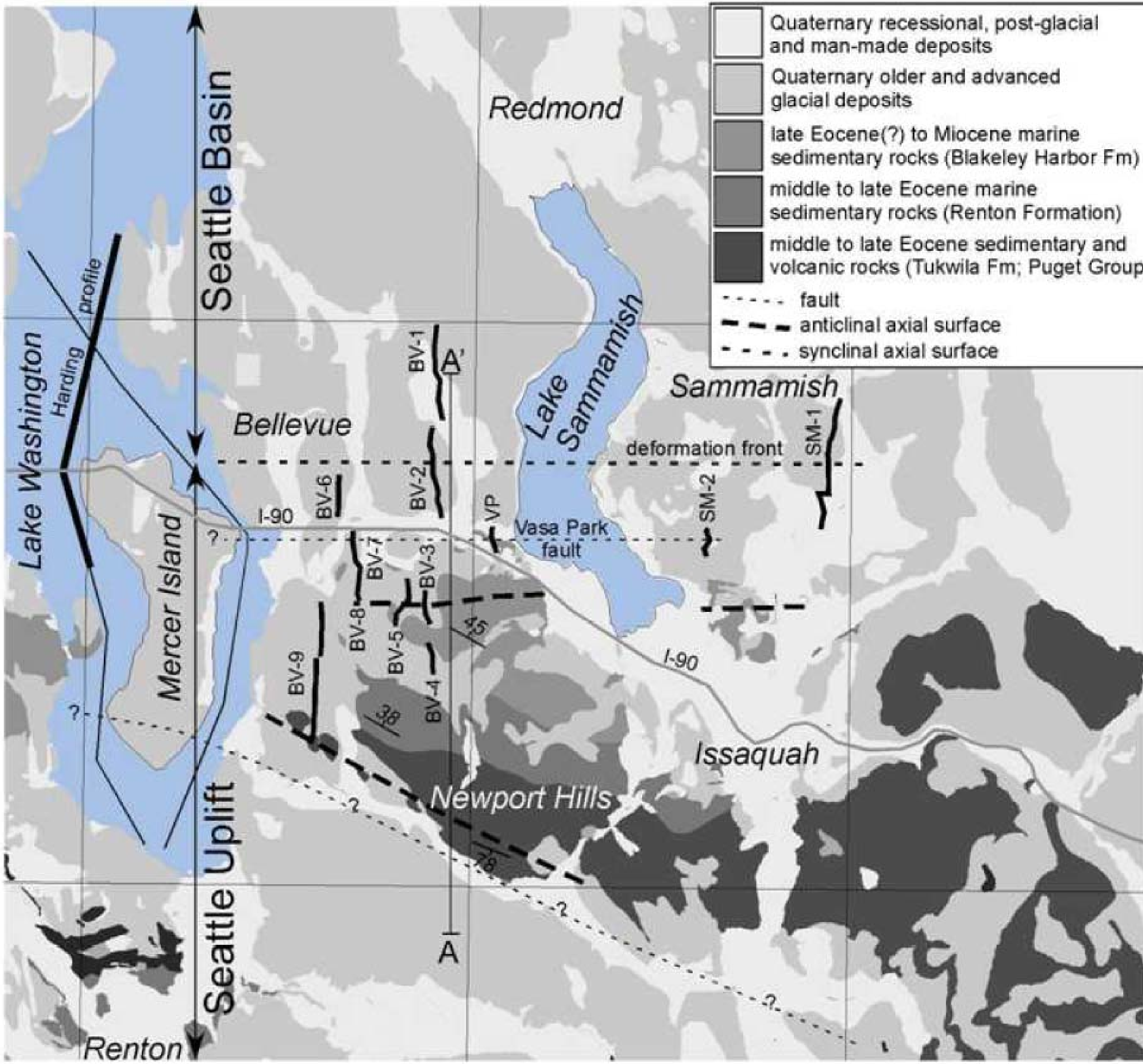


This structural model (from T. Pratt, USGS)shows several places where the fault ruptures to the surface along this north-south profile



This seismic reflection profile in Lake Washington shows the kind of data from which this structural model is developed





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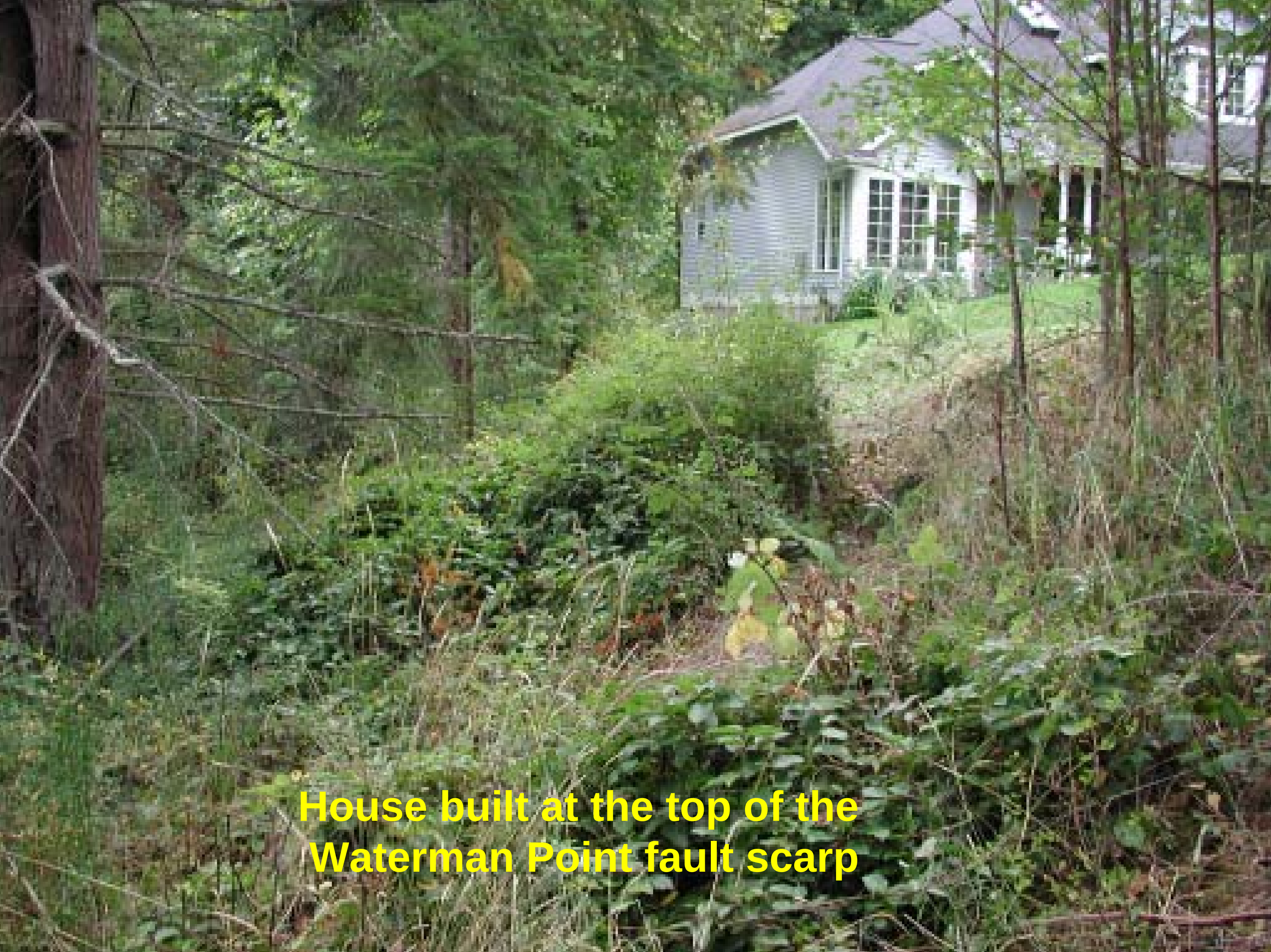

House built at the top of the
Waterman Point fault scarp

Old growth forest in Lake Washington

- **Earthquake-induced landslides in Lake Washington drowned old Growth Forests about 1,000 years ago**

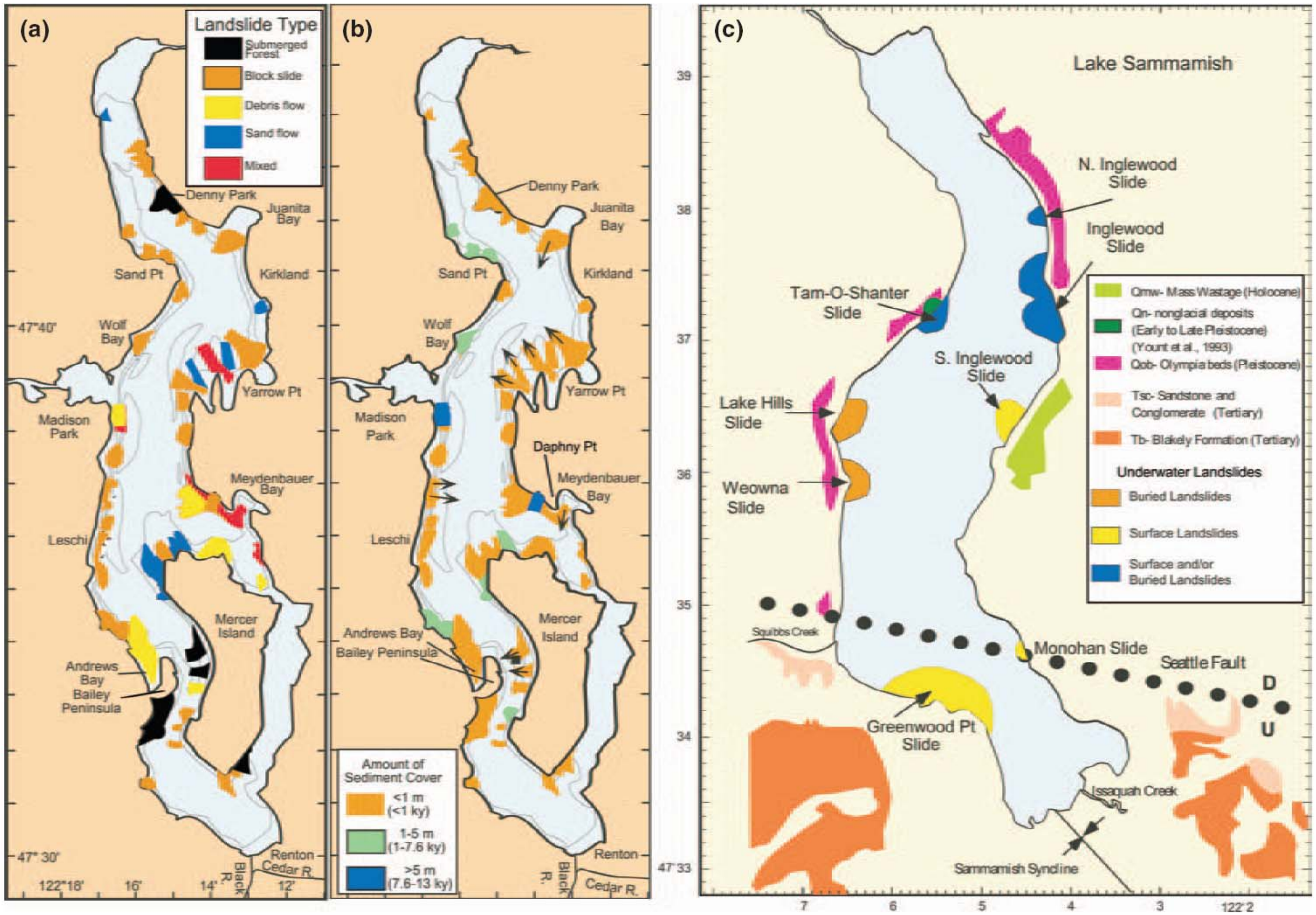
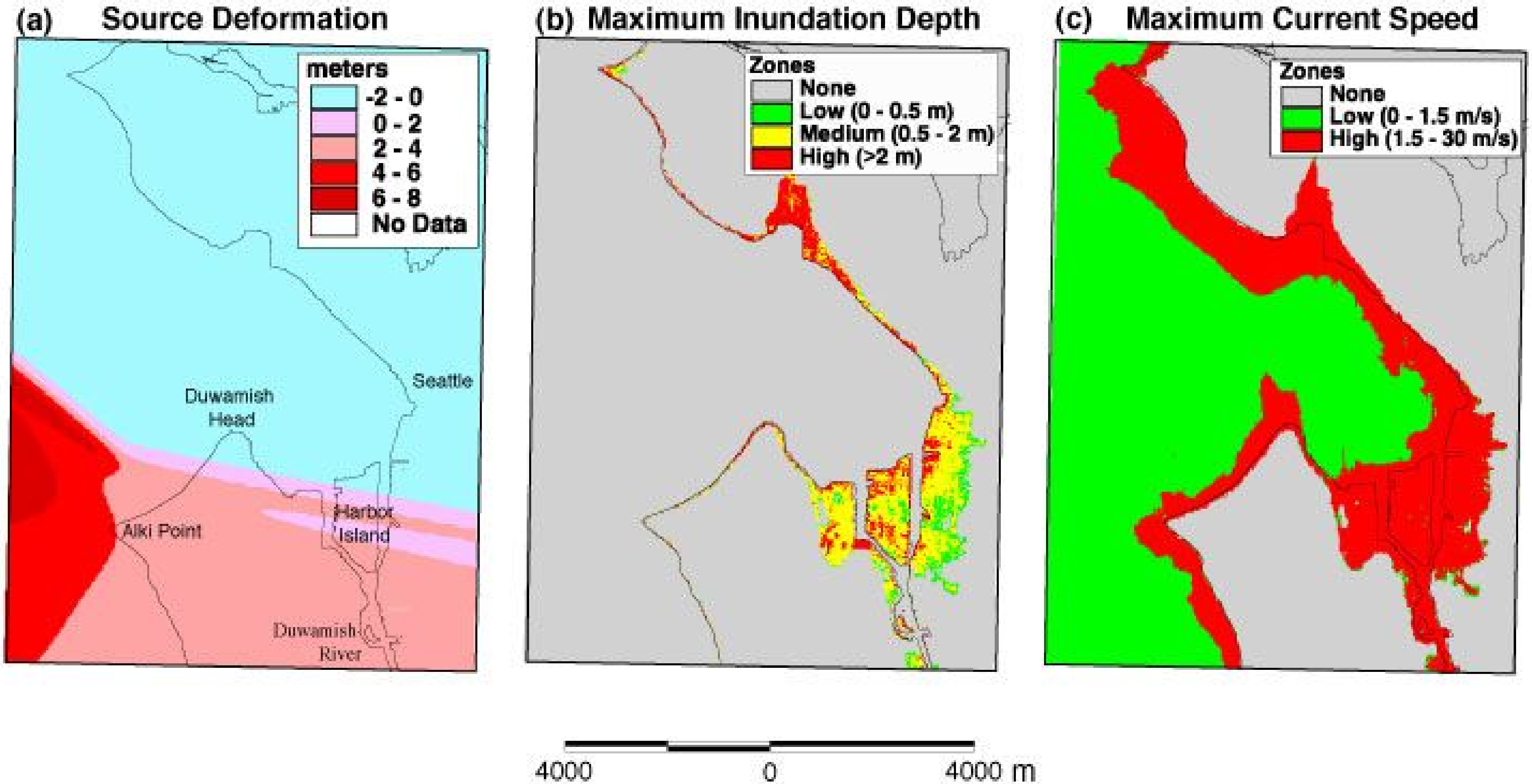


Figure 4: (a) Lake Washington subaqueous landslides mapped from high-resolution single channel seismic reflection profiles and swath sidescan imagery, and classified into submerged forests, coherent block slides, debris flows, sand flows, and mixed slumps. (b) Lake Washington subaqueous landslides classified by age. (c) Lake Sammamish geologic map, showing underwater landslides, onland exposures of pre-Frasier geology, and Holocene mass wasting.



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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
OPEN FILE REPORT 2003-14

Tsunami Hazard Map of the Elliott Bay Area, Seattle, Washington: Modeled Tsunami Inundation from a Seattle Fault Earthquake

by
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2003

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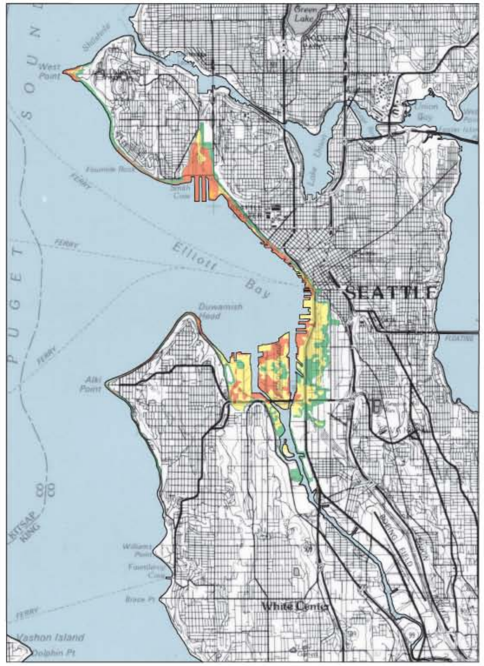
Vasily.Titov@noaa.gov, Angie.J.Venturato@noaa.gov, Harold.Mofjeld@noaa.gov, Frank.I.Gonzalez@noaa.gov



Depth of inundation: 0–.5 meters .5–2 meters 2–5 meters

SCALE 1:50,000

MAP LOCATION

INTRODUCTION

In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the West Coast from tsunamis generated locally. A panel of representatives from NOAA, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS) and the five Pacific coast states wrote the plan and submitted it to Congress, which created the National Tsunami Hazard Mitigation Program (NTHMP) in October of 1996. The National Tsunami Hazard Mitigation Program is designed to reduce the impact of tsunamis through warning guidance, hazard assessment, and mitigation. A key component of the hazard assessment for tsunamis is delineation of areas subject to tsunami inundation. This map is part of a series of tsunami inundation maps produced by the Washington Department of Natural Resources, Division of Geology and Earth Resources, in cooperation with the Washington Emergency Management Division, as a contribution of the National Tsunami Hazard Mitigation Program (Walsh and others, 2003a,b; 2002a,b; 2000). These maps are produced using computer models of earthquake-generated tsunamis from nearby seismic sources. The modeling for this map was done by the Center for the Tsunami Inundation Mapping Efforts (TIME) at NOAA's Pacific Marine Environmental Laboratory in Seattle for a scenario earthquake on the Seattle fault.

THE SEATTLE FAULT

Geographic features now known to be associated with the Seattle fault have been noted for many years. Vancouver (1798) noted that the fault-uplifted bedrock wavecut platform at Restoration Point (Fig. 1, Location 1) on Bainbridge Island "did not possess that beautiful variety of landscape, being an almost impenetrable wilderness of lofty trees" that characterized the rest of his explorations in Puget Sound. Kimball (1897) described the Newcastle Hills (Fig. 1, Location 2), part of the hanging wall of the fault, as a "postglacial eruption". Danes and others (1965) interpreted the large gravity and magnetic anomalies through central Puget Sound and the associated abrupt change in the sedimentary section thickness as an active fault with about 11 km of displacement. Rogers (1970) collected additional gravity and magnetic data across the structure and named it the Seattle-Bremerton fault. Gower (1978) demonstrated that the uplift at Restoration Point (Fig. 1, Location 1) was Holocene in age and Bucknam and others (1992) showed that there was an uplift of 7 meters produced on the fault about 1,000 years ago.

In 1996, the first of a series of lidar (Light Detection And Ranging) surveys was flown over Bainbridge Island. This and subsequent lidar missions have enabled scientists to locate splays of the fault in a number of places accurately enough to dig trenches (Bucknam and others, 1999; Nelson and others, 2002). Lidar mapping and trenching have enabled scientists to accurately map the amount of uplift on the fault in some places. Also in 1996, the U.S. Geological Survey began several large-scale geophysical studies. An aeromagnetic study of the Puget Sound (Blakely and others, 1999, 2002) enabled more accurate location of the fault along its entire length. Seismic reflection and tomographic studies, such as SHIPS (Seismic Hazards Investigations in Puget Sound) and other geophysical studies in Puget Sound have greatly increased the understanding of the fault characteristics at depth (Pratt and others, 1997; Johnson and others, 1999; Brocher and others, 2001; ten Brink and others, 2002; Van Wagoner and others, 2002), although considerable uncertainties and controversy remain.

There also is substantial evidence that earthquakes on the Seattle fault can generate tsunamis. Atwater and Moore (1992) showed that tsunamis inundated part of Whidbey Island (Fig. 1, Location 5) and West Point (Fig. 1, Location 4) about 1000 years ago, and Jacoby and others (1992) showed that a tree in the tsunami deposit at West Point died in the same season of the same year as a drowned forest carried into Lake Washington by a huge landslide from Mercer Island, strongly implicating the A.D. 900–930 event. A discontinuous sand layer along Snohomish delta distributaries—Ebey Slough, Steamboat Slough, Union Slough, and Snohomish River (Fig. 1, Location 6)—also probably was deposited by the tsunami from the large A.D. 900–930 earthquake on the Seattle fault (Bourgeois and Johnson, 2001).

MODELING

Tsunami inundation shown on the map is based on a computer model of waves generated by the Seattle fault (Titov and others, in press). The model used is the finite difference model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and González, 1997). It uses a grid of topographic and bathymetric elevations and calculates a wave elevation and velocity at each gridpoint at specified time intervals to simulate the generation, propagation and inundation of tsunamis in the Elliot Bay area.

In this MOST model study, the tsunami is generated by a Seattle fault deformation model that simulates the A.D. 900–930 event as a credible worst-case scenario of magnitude 7.3. The magnitude was chosen to be consistent with the 2002 USGS update of the National Seismic Hazard Maps (Frankel and others, 2002). Parameter values are based on Brocher and others (2001), Calvert and Fisher (2001), and ten Brink and others (2002).

Table 1. Segment (west to east) parameters for magnitude 7.3 Seattle fault earthquake models. The vertical deformation pattern is shown in Figure 1.

Segment	Depth (km)	Length (km)	Width (km)	Strike (°)	Dip (°)	Slip (m)
1	0.5	15.2	20	87.9	60	1
2	0.5	6.3	20	86.6	60	1
3	0.5	8.9	20	96.0	60	12
4	0.5	3.2	20	128.8	60	11
5	0.5	11.5	20	99.3	60	4
6	0.5	14.9	20	81.0	60	1

The slip distribution was constrained, through trial-and-error, to match available field estimates of vertical displacement at three sites—Alki Point (Fig. 1, Location 3; +4 m), Restoration Point (Fig. 1, Location 1; +7 m) and West Point (Fig. 1, Location 4; -1 ±0.5 m).

Titov and others (in press) also modeled a M7.6 event, and the tsunami inundation values and patterns were essentially the same as for the M7.3 event. No doubt this is due to the fact that the deformation patterns and values were very similar for both events, since they were each constrained by field data at the three sites. Also, the smaller ground displacement zone of the M7.3 event forms a more concentrated tsunami source that compensates for its smaller overall displacement.

The computed tsunami inundation is shown on the map in three color-coded depth ranges—0–0.5 m, 0.5–2 m, and greater than 2 m. These depth ranges were chosen because they are approximately knee-high or less, knee-high to head-high, and more than head-high. The limit of tsunami inundation is the landward edge of the green zone. In previous maps, we have shown only the edge of inundation, but for this map, much higher resolution bathymetric and topographic data were available. Figure 2 also shows current velocities in two zones—less than or greater than 1.5 meters/second (~3 miles/hour), which is the current speed at which it would be difficult to stand. Within this zone, computed velocities locally exceed 20 meters/second (~40 miles/hour). Computed wave heights in Elliott Bay were approximately 6 meters. Figure 3 shows a time progression of the wave across Elliott Bay at 30-second intervals. Note that because Harbor Island is uplifted by the earthquake, the Duwamish Waterway initially drains rapidly before the wave reflects off the north side of the bay and then inundates the Harbor Island area.

LIMITATIONS OF THE MAP

Because the nature of the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this modeling was selected to honor the paleoseismic constraints, but the next Seattle fault earthquake may be substantially different from these. Sherrod and others (2000) show that an uplift event at Restoration Point predating the A.D. 900–930 event was smaller. Trenching of subsidiary structures to the Seattle fault that are thought to be coseimic with the main fault trace (Nelson and others, 2002) indicate that there were at least two earthquakes in the 1500 years before the A.D. 900–930 event. These, however, did not produce prominent uplifted wavecut platforms similar to the one made by the A.D. 900–930 event, suggesting that significant earthquakes have occurred on the fault that had different and smaller uplifts in central Puget Sound.

Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. This can be up to 50 meters horizontally, although high-resolution multibeam data (Gardner and others, 2001) is available for Elliot Bay and 2-foot contour topography is available for the city of Seattle.

The model run does not include the influences of changes in tides and is referred to mean high water. The tide stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community. In Elliott Bay, the mean spring tide range is about 11 feet and can be as much as about 16 feet (NOAA, accessed at http://co-ops.nos.noaa.gov/co-ops.html, June 25, 2003). This means that, while the modeling can be a useful tool to guide evacuation planning, it is not of sufficient resolution to be useful for land-use planning.

ACKNOWLEDGMENTS

This project was supported by the National Tsunami Hazards Mitigation Program (NTHMP) in cooperation with the city of Seattle and the Washington Emergency Management Division. Information about NTHMP is available at http://www.pmel.noaa.gov/tsunami-hazard/. Discussions with Tom Pratt, Brian Sherrod, and Craig Weaver (all USGS, Seattle) were invaluable for calibrating the fault source model. Karl Wegmann and Steve Palmer, both Washington Division of Geology and Earth Resources, provided helpful reviews.

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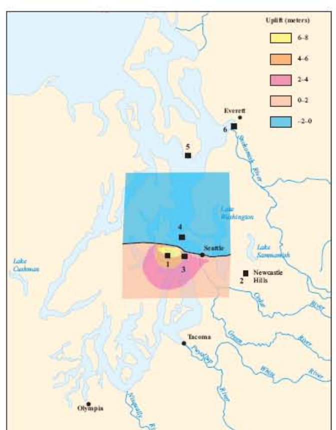
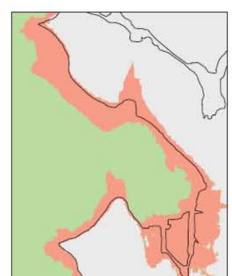


Figure 1. (left) Map showing Seattle fault and associated ground deformation model used in this study. Numbered locations are localities mentioned in text. 1, Restoration Point; 2, Newcastle Hills; 3, Alki Point; 4, West Point; 5, Cultus Bay; 6, Snohomish Delta.



Current velocity: none; medium <1.5 m/s; high >1.5 m/s

Figure 2. Computed current velocity zones. Note that velocities are highest along the shoreline and in narrow channels. One meter/second is ~2.2 mph.

Figure 3. Freeze frames of animation of modeled tsunami at 30-second intervals (from left to right). The wave crest is colored pale blue. Note that because Harbor Island is uplifted by the earthquake, the Duwamish Waterway initially drains rapidly before the wave reflects off the north side of the bay and then inundates the Harbor Island area.

The phenomenon we call "tsunami" (soo-NAH-mee) is a series of traveling ocean waves of extremely long length generated by disturbances associated primarily with earthquakes occurring below or near the ocean floor. Underwater volcanic eruptions and landslides can also generate tsunamis. In the deep ocean, their length from wave crest to wave crest may be a hundred miles or more but with a wave height of only a few feet or less. They cannot be felt aboard ships nor can they be seen from the air in the open ocean. In deep water, the waves may reach speeds exceeding 500 miles per hour.

Tsunamis are a threat to life and property to anyone living near the ocean. For example, in 1992 and 1993 over 2,000 people were killed by tsunamis occurring in Nicaragua, Indonesia and Japan. Property damage was nearly one billion dollars. The 1960 Chile Earthquake generated a Pacific-wide tsunami that caused widespread death and destruction in Chile, Hawaii, Japan and other areas in the Pacific. Large tsunamis have been known to rise over 100 feet, while tsunamis 10 to 20 feet high can be very destructive and cause many deaths and injuries.

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